THE MIDDLE-LATE TRIASSIC $\delta^{13}C_{plant}$ TREND AND THE CARNIAN PLUVIAL EVENT C-ISOTOPE SIGNATURE (Summary of the PhD thesis)

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Note to the reader

This is a summary of the PhD thesis defended in March 2011 and thus does not take into account the important literature published in the following years. The work from this thesis has been published in high impact factor journals (e.g. *Geology*) during and immediately after my PhD. Following this study a number of papers have been published during the 2012–2014 with the aim of better understanding Carnian climate and making the Dolomites a reference area for the study of the Carnian Pluvial Event.

ABSTRACT

After the Permian/Triassic mass extinction, the Early – lowermost Middle Triassic carbon cycle was extremely unstable. The global $\delta^{13}C_{carb}$ curve shows a series of large short-term excursions, tentatively associated to a limited biological recovery that characterized this time interval. Carbonate carbon isotopic values seem to stabilize during the Anisian (Middle Triassic), when a Middle – early Late Triassic positive secular trend of 3–4 ‰ begins. This $\delta^{13}C$ rise has been linked to the re-establishment of carbon burial and the re-emergence of coal-swamps. By the end of the Early Carnian (Julian), the $\delta^{13}C$ of carbonates reached its maximum values of ca. 3.5 ‰ when a short-term climatic episode of late Julian age is documented worldwide from tropical latitudes, the "Carnian Pluvial Event" (CPE), is characterized by the demise of rimmed carbonate platforms, an increase of coarse terrigenous input, paleosols indicative of a humid climate and a rise of the

Carbonate Compensation Depth (CCD) in the deep Tethys sea. Such characteristics are similar to those of Jurassic and Cretaceous Oceanic Anoxic Events (OAE) that are marked by significant perturbations of the carbon cycle. This work aimed to build a Middle – early Late Triassic $\delta^{13}C$ curve based on terrestrial organic matter (wood, leaves and biomarkers) and tests the hypothesis of a carbon isotope shift associated to the CPE.

Results shows that terrestrial organic matter $\delta^{13}C$ values from the Middle Triassic are offset by approx. 3‰ with respect to the Late Triassic: Anisian and Ladinian values vary between -27‰ to -23.5‰ compared to the Carnian values ranges of -24‰ to -19.5‰. These data confirms a 3‰ $\delta^{13}C_{carb}$ excursion from the Middle to the beginning of the Late Triassic is also recorded by terrestrial organic matter.

In a stratigraphic succession (Milieres-Dibona section) of the Dolomites, a sharp negative $\delta^{13}C_{org}$ excursion at the onset of the CPE is observed for the first time. The abrupt carbon isotope excursion (-4‰) is recorded by leaf waxes *n*-alkanes and total organic carbon (-2‰). This shift testifies for a rapid injection of CO_2 with a light C-isotope composition into the atmosphere. This new dataset confirm the hypothesis that the CPE was a global event. It is proposed that the carbon isotope negative shift was triggered by the eruption of the coeval Wrangellia flood basalts with strong consequences for the environments and biosphere, e.g. the demise of carbonate platforms, extinctions and radiations of some of the most important Mesozoic groups.

Rationale

At the end of the early Carnian (Julian), a short-term major climatic change is documented worldwide (Preto et al., 2010). This episode, known as **"Carnian Pluvial Event"** (CPE; Simms and Ruffell, 1989), has been very well dated to a short stratigraphic interval corresponding to the uppermost Julian – lowermost Tuvalian (Carnian, Late Triassic) by ammonoids, palynomorphs and conodonts, and its minimum U/Pb absolute age has been given by Furin et al. (2006) to be

230.91±0.33 Ma. The sedimentological and palaeontological features characterizing the CPE have been attributed to a shift from the general arid climate of the Late Triassic to more humid conditions (e.g. Schlager and Schöllnberger, 1974; Simms and Ruffel, 1989; Keim et al., 2001; Roghi 2004; Hornung and Brandner 2005; Keim et al., 2006; Hornung et al., 2007a, 2007b, 2007c; Breda et al., 2009; Preto et al., 2010; Stefani et al., 2010; Roghi et al., 2010). At least three (Breda et al., 2009; Stefani et al., 2010) to four (Roghi et al., 2010) distinct humid pulses have been recognized so far to constitute the CPE. The CPE is marked by major sedimentological changes in continental – deep water palaeoenvironments, for example the demise of rimmed carbonate platforms, an increase of coarse terrigenous fraction, black shale deposition and paleosols indicative of a relatively humid climate, and a rise of the Carbonate Compensation Depth (CCD) in the deep Tethys (Preto et al., 2010 and references therein). A biological turnover has been recognized both in terrestrial and marine realms. A clear shift from xerophytic to hygrophytic palynological assemblages, i.e. from assemblages reflecting vegetation growing under arid and humid conditions respectively, has been recognized during the CPE (Roghi 2004; Roghi et al., 2010). Associated to this floral change a lot of amber (fossil resin) has been found in Carnian deposits of Europe (Southern Alps, Itay; Northern Calcareous Alps (NCA), Austria; Balaton Highland, Hungary); Arizona, North America; Argentina, South America and Leshoto, South Africa (Gianolla et al., 1998; Roghi et al., 2006). The CPE is marked also by high extinction rates among ammonoids, crinoid, briozoa (Simms and Ruffel 1989, 1990; Simms et al., 1995) and conodonts (Simms and Ruffel, 1989; Rigo et al., 2007). The magnitude of the extinction is minor when compared to the biggest mass extinctions during the Phanerozoic (Rohde & Muller 2005). However, the CPE may have had a key role in the origin and/or radiation of some of the most important groups in Mesozoic ecosystems. The first known dinosaurs were found in the Carnian of the Ishigualasto Fm. (Argentina) (Martinez et al., 2011) and have an absolute age very similar to that of the CPE (Rogers et al., 1993; Furin et al., 2006). The first calcareous nannoplankton also dates back to the Carnian (Erba, 2006) and the radiation of modern-like conifers occurs during the Late Triassic (Taylor et al, 2009). The Carnian seems to have been also crucial for the evolution of scleractinian corals that started to be important constituents of the reefs (Stanley, 1988, 2003). Such characteristics make the CPE an event very similar to those of Jurassic and Cretaceous Oceanic Anoxic Events (OAE) that are also characterized by significant perturbations of the carbon cycle (e.g. Jenkyns 2010). The CPE occurs at the maximum of a long-term 3–4‰ positive carbon isotope trend that begun after the Early – lowermost Middle Triassic carbon cycle instability that could be tentatively associated to a limited biological recovery that characterized this time interval (Payne et al., 2004; Korte et al., 2005). The Middle – early Late Triassic $\delta^{13}C$ rise has been linked to the re-establishment of carbon burial due to the re-emergence of coal-swamps (Korte et al., 2005).

The main goal of the PhD project was to test whether any major carbon isotope shift was associated to the CPE by using high resolution and cutting-edge techniques for the carbon isotope analysis of the organic matter.

The sedimentological effects of the CPE stand out dramatically in the Dolomites making this area a natural laboratory for the study of this peculiar event. Moreover, large areas of the Dolomites experienced little burial, which likely did not altered the pristine organic matter and is a key requirement to run reliable organic geochemistry analyses.

Scientific approach

The first part of the PhD was devoted to the development of an appropriate methodological approach to be used to build a solid and reliable Carnian $\delta^{13}C_{org}$ curve. Fossil organic matter carbon isotope signature is the result of complex fractionation processes that affect the $^{12}C/^{13}C$ ratio during and after the production of organic compounds and must be considered for a correct interpretation of $\delta^{13}C_{org}$ curves, especially those from deep time.

In recent years, researchers have performed C-isotope analyses of many types of specific structures and compounds exclusively associated with terrestrial land plants, including wood (e.g., Hesselbo et al., 2007), cuticles (e.g., Arens and Jahren, 2000) and pollen (e.g., Jahren, 2004), to reconstruct the carbon isotope changes of atmospheric CO_2. Plant $\delta^{13}C$ is the result of three fractionation processes of the atmospheric C: 1) fractionation during the photosynthesis, 2) post-photosynthetic fractionation, 3) diagenetic fractionation. Following the Farquhar model (Farquhar et al., 1989), three important factors influence the carbon isotope composition of C3 vascular plant (the only present in the Mesozoic) during photosynthesis: 1) physical and biochemical fractionation occurring before and during carboxylation; 2) ecological factors such as water stress (3–6‰ positive shift), nutrients shortage (4‰ negative), light limitation (5–6‰ negative) and temperature (3‰ negative) (Arens et al., 2000); 3) the carbon isotope composition of the atmosphere ($\delta^{13}C_{atm}$). The interplay of these factors produces highly variable carbon-isotope signatures in modern C3 plants and their component parts (wood, cuticles, resin, etc.), with $\delta^{13}C$ values varying from -19‰ to -35‰ (Tipple and Pagani, 2007). Similar variability is to be expected in the fossil record, potentially compromising palaeoclimatic reconstructions based on organic $\delta^{13}C$. Despite these limitations, Jahren et al. (2008) experiments on living plants demonstrate a good correlation in $\delta^{13}C_{atm}$ and $\delta^{13}C_{plant}$, and this suggests that carbon isotope values from fossil plants can be used as a proxy for $\delta^{13}C_{atm}$ across a range of pCO_2 levels.

The study of molecular fossils (biomarkers) is a relatively new frontier for palaeoecology and palaeoclimatology studies. *N*-alkanes (normal alkanes; straight-chain saturated hydrocarbons) with chain lengths of C_{25} - C_{35} and odd-over-even carbon-number distribution derive from epicuticular waxes of terrestrial higher plants (Peters et al., 2005). These lipids are common in both marine and continental sediments and very resistant to diagenesis. Their carbon isotope signature has been successfully used to study $\delta^{13}C$ shifts associated with major events such as the P/T mass extinction (Xie et al., 2007) or the Paleocene/Eocene Thermal Maximum (Pagani et al., 2006); to determine the advent of the C4 photosynthetic pathway (Tipple and Pagani, 2007); or to study the relative proportions of C3 and C4 plant material in sediments (Pancost and Boot, 2004, and references therein). $\delta^{13}C$ analysis of *n*-alkanes partially overcomes issues associate with the large $\delta^{13}C$ range in plants (see above), as they pool together the contribution of numerous individual plants, and thus have maximum statistical significance.

Study area

The Dolomites are one of the most classic areas for the study of the Triassic, with their outstandingly exposed and spectacular sedimentary successions. For this reason stratigraphic sections have been selected in the Dolomites, measured, sampled and analysed for carbon isotopes. A supporting stratigraphic section has been chosen in the Julian Alps. Amber from all around the world has been also collected to compare the results obtained from amber found in the Dolomites. Triassic sediments were selected with ages ranging from the Anisian to the Carnian.
A succession of hemipelagic limestones and marls (Dont Formation) containing ammonoids and other marine fossils along with plant remains, is exposed at **Monte Prà della Vacca - Kühwiesenkopf in the north-eastern Dolomites**. Samples of plant tissue analysed in this study derive from a horizon containing both marine and terrestrial fossils, dated to the middle-late Pelsonian (Anisian) by ammonoid and palynomorph biostratigraphy (Broglio Loriga et al., 2002; Kustatscher et al., 2006). A newly investigated outcrop of upper Ladinian deep-water volcaniclastic siltites and arenites (Wengen Formation) in the **central Dolomites, near the village of Caprile in the Cordevole Valley**, is identified here as "locality Savinér". Abundant plant remains were found in the outcrop and as debris in this locality. A third set of samples was collected in shallow-water limestones and marls of the Rio del Lago Formation near Dogna, in the Dogna Valley of eastern Southern Alps. This formation represents the middle portion of a mixed carbonate-siliciclastic ramp of early Carnian age (Preto et al., 2005). Abundant plant remains were collected in a fine marly limestone bed at the base of the formation. Samples of wood, leaves, amber, claystone and marlstone were collected also at **Rifugio Dibona (Tofane mountains) near Cortina d'Ampezzo in the central Dolomites**. This section consists of carbonates, shales and arenites (Heiligkreuz Fm., formerly Dürrenstein Fm.) deposited in a marginal marine setting between the end of the early

Carnian and the beginning of the late Carnian (Preto and Hinnov, 2003). Cretaceous Amber samples come from several sections in Spain and France, and from the Grassy Lake deposit in Canada (see full PhD thesis for the description of all the localities).

Methods

Geochemical analyses were made in collaboration with the Universities of Oxford, Bristol and Leeds in UK.

To study the C-isotope variability of different organic matter compounds and tissues, wood, leaves, amber from stratigraphic sections of the Middle - lower Upper Triassic of the Southern Alps (Italy) were collected. These plant remains were hand picked from disgregated or undisturbed rock, powdered and treated with HCl in order to remove carbonates and pyrite. Wood, leaves and amber powders C-isotope signatures were measured at the University of Oxford (UK): an aliquot of 1.5 mg of sample was weighed, embedded in tin capsules and analyzed at the Research Laboratory for Archaeology and the History of Art (University of Oxford) with a Carlo Erba NA 1108 elemental analyser coupled to a SERCON Geo 20/20 IRMS running in continuous flow mode with a He carrier gas (flow rate 100 ml per min) using an alanine in-house standard routinely checked against international standards IAEA-CH- 6 and IAEA-CH-7 and traceable back to the VPDB standard. All results are accurate to better than ±0.15‰ (σ).

Claystones and marlstones have been collected for bulk organic matter (OM) and compound-specific carbon isotope analysis. For bulk OM analysis rock powders were acid washed in ~1.2 M HCl overnight, before washing in distilled water and drying. The resulting powders were weighed into tin cups and the C-isotope analyses were performed at the University of Leeds (UK): organic carbon was quantitatively converted to CO_2 by flash combustion at 1020°C in the presence of pure O injected into a stream of He. Excess O was removed by reaction with hot copper wires at 650°C, water was removed in a magnesium perchlorate trap and the CO_2 separated from other impurities using a chromatographic column. $^{12}C/^{13}C$ is derived from the integrated mass 44, 45 and 46 signals from the pulse of sample CO_2, compared to those in an independently introduced pulse of CO_2 reference gas. These ratios are calibrated using international standards ANU-sucrose (-10.47‰) and IAEA-CH7 (polyethylene film, -31.83‰). The precision obtained for repeat analysis was better than ± 0.2‰ (σ). See Table DR2 and Table DR3 for a complete list of all TOC and wood C-isotopic data. For compound specific isotope analysis rocks were cleaned with methanol and then ground using a pestle and mortar. Biomarkers were extracted and analyses at the University of Bristol (UK). The sediments were extracted by using dichloromethane and methanol (DCM:MeOH 2:1 v/v) in a Soxhlet apparatus. The total lipid extract was separated into neutral fraction using dichloromethane/iso-propanol (DCM/iPA 2:1 v/v) and acid fraction using aminopropyl solid phase extraction columns with MeOH and 2% acetic acid in ether. Neutral fractions were further separated into apolar (hexane/DCM 9:1 v/v) and polar (DCM/MeOH 1:2 v/v) fractions using alumina flash column chromatography. Compounds $\delta^{13}C$ was analysed in duplicate (σ = 0.1 to 1.8, see Table DR1) using an Agilent 6890 gas cromatographer coupled with a Finnigan MAT DeltaPLUSXL isotope ratio mass spectrometer (GC-IRMS). Separation of compounds was achieved using a Non Polar column HP1 (50 m x 0.32 mm internal diameter). GC oven temperature was programmed from 70° C to 130° C at a rate of 20° C/min, then from 130° C to 300° C (rate: 4° C/min) and finally hold at 300° C for 25 min.

Results and conclusions

Fossil plant remains C-isotope analyses

Triassic amber, wood and leaf $\delta^{13}C$ values lie in a large range within the same beds (~ 2-5‰). Carnian ambers have $\delta^{13}C$ values similar to the associated wood but with a larger range of variability than wood and leaves. These restricted wood and leaf $\delta^{13}C$ ranges can be explained by selective degradation of plant OM during the fossilization processes. Despite the high variability, wood and leaf $\delta^{13}C$ values register a positive trend between the Middle and early Late Triassic that is consistent with existing marine inorganic carbon-isotope data from skeletal calcite. This parallel trend suggests that Triassic brachiopod calcite and marine carbonates faithfully registered the secular carbon-isotope evolution of the ocean–atmosphere system.

The range of values in Triassic amber $\delta^{13}C$ is comparable with that obtained for recent resins. Thermogravimetric analyses coupled with C-isotope measurements show that alteration processes doesn't change the $\delta^{13}C$ of amber even if it caused important transformations of the main components. Data suggest that the pristine carbon-isotope signature is not altered by resin maturation during diagenesis, unlike other plant-derived materials as wood and leaves.

Cretaceous $\delta^{13}C_{amber}$ data register secular trends consistent with inorganic carbonate C-isotopes data. Results show that amber is potentially a very solid tool for C-isotopes – based studies with palaeoenvironmental, palaeoclimatic and stratigraphic purposes.

Biomarker analysis

Biomarker and non-biomarker maturity parameters show that extracted lipids have experienced a moderate thermal maturation and that the source of OM was mostly terrestrial. Long chain n-alkanes (n-$C_{25\text{-}33}$) show an odd-over-even distribution that is typical of an higher-plant source.

N-alkanes have $\delta^{13}C$ values ranging from -21.08‰ to -30.97‰. Odd n-$C_{25\text{-}33}$ n-alkanes have C-isotope values in the range expected for C3 plant and are more depleted in ^{13}C than bulk wood coming from the same stratigraphic layers, in agreement with $\delta^{13}C$ measurements of Recent material. $\delta^{13}C$ of n-$C_{25\text{-}33}$ is also more depleted than $\delta^{13}C_{TOC}$. The C-isotope offset of n-alkenes vs TOC increases as values become more depleted.

Isoprenoids $\delta^{13}C$ ranges from -23.17‰ to -33.5‰. Difference between the C-isotope signature of pristane and phytane can be explained by different sources.

N-alkanes and isoprenoids draw a positive secular C-isotope shift during the latest Ladinian - early Carnian interval that is consistent with $\delta^{13}C$ wood and marine carbonates.

An abrupt negative $\delta^{13}C$ shift is registered by all extracted n-alkanes and isoprenoids within the A. austriacum ammonoid subzone.

The CPE carbon isotope signature

Within the positive Middle –early Late Triassic trend, higher plant n-C_{25-33} n-alkanes and TOC $\delta^{13}C$ values reveal a sudden and pronounced negative shift of ~-4‰ and ~-2‰ respectively, in the lower part of the Heiligkreutz Formation corresponding to the lower *Austrotrachyceras austricum* ammonoid biochronozone (uppermost lower Carnian).

These new C-isotope data clearly show that during the CPE, CO_2 enriched in ^{12}C was injected into the exchangeable reservoirs of the active C-cycle (atmosphere-ocean-land). One possibility for this is CO_2 release by the coeval Wrangellia LIP, either by direct injection of magmatic CO_2 or by triggering additional CO_2 release from other light carbon reservoirs as, e.g., methane chlathrate deposits on continental shelves. Key to this association is the timing of Wrangellia eruption: biostratigraphic data constrain Wrangellia volcanism to the late Ladinian – late Carnian. Sediments underlying basalts contain Ladinian bivalves belonging to the genus *Daonella* (Greene et al., 2010) and overlying sediments present a lower Tuvalian (upper Carnian) ammonoid association with *Tropites dilleri* (Tozer et al., 1994). Most of the existing absolute Ar/Ar ages of Wrangellia basalts are reset to ages younger than that of deposition (Greene et al., 2010 and references therein). Some U/Pb age however agree with Wrangellia basalts biostratigraphic constrains (Greene et al., 2010) and are very similar to the existing absolute minimum age for the CPE (Furin et al., 2006).

Sedimentological evidence from CPE sections supports the hypothesis of rapid injection of CO2 into the atmosphere-ocean system: a rapid influx of CO_2 results in the acidification of seawater and has a strong impact on the stability and production of carbonates. A rise of the CCD (Carbonate Compensation Depth) observed in the Lagonegro basin of western Tethys and the crisis of carbonate sedimentation from shallow water to deep water settings at the CPE (Rigo et al., 2007) are best explained by a decrease in the pH of seawater. A rise of the CCD is also associated with events such as the Early Aptian Oceanic Anoxic Event (Erba et al., 2010) and the Paleocene-Eocene Thermal Maximum (Zachos et al., 2005). In contrast to these events however, the CPE occurred during a time of "aragonite seas" (Stanley and Hardie 1998) when seawater chemistry was more similar to Recent than that of the Cretaceous and Paleocene/Eocene "calcite sea" (Hardie 1996; Ries 2010; Hasiuk and Lohmann, 2010).

The discovery of an intense, rapid negative carbon isotope excursion shed new light on the nature of the CPE and lined it up to the major known climatic perturbations of the Mesozoic and Cenozoic. The hypothesis that the CPE is a consequence of the eruption of Wrangellia LIP finds solid bases and a new tessera is offered to support the link between LIP onset and global climate changes in Earth history.

The Dolomites provided the perfect opportunity to study the Carnian Pluvial Event and continues to contribute significantly to the understanding of Triassic climate and biota evolution.

Published papers from the PhD thesis

The results of the PhD thesis have been published in 3 peer-reviewed international journals. In particular, the study of the carbon isotope variability of Triassic amber, wood and leaves and the Middle – Early Late Triassic carbon isotope positive trend has been published in *Palaeogeography, Palaeoclimatology, Palaeoecology* (IF: 2.745), the study on the carbon isotope signature of the Carnian Pluvial Event in *Geology* (IF: 4.087) and the study of the Cretaceous amber in *Geologica Acta* (IF: 1.262).

Cited references

Arens, N.C., Jahren, A.H., 2000. Carbon Isotope Excursion in Atmospheric CO2 at the Cretaceous- Tertiary Boundary: Evidence from Terrestrial Sediments. Palaios 15, 314-322.

Arens, N.C., Jahren, A.H., Amundson, R., 2000. Can C3 plants faithfully record the carbon isotopic composition of atmospheric dioxide?. Paleobiology 26, 137-164.

Breda, A., Preto, N., Roghi, G., Furin, S., Meneguolo, R., Ragazzi, E., Fedele, P., Gianolla, P., 2009. The Carnian Pluvial Event in the Tofane area (Cortina D'Ampezzo, Dolomites, Italy). Geo.Alp 6, 80-115.

Broglio-Loriga, C., Fugagnoli, A., Van Konijnenburg – van Cittert, J.H.A., Kustatscher, E., Posenato, R., Wachtler, M. 2002. The Anisian Macroflora from the Northern Dolomites (Kühwiesenkopf / Monte Pra della Vacca, Braies): a first report. Rivista Italiana di Paleontologia e Stratigrafia 108 (3), 381-389.

Erba et al., 2010

Erba, E., 2006. The first 150 million years history of calcareous nannoplankton: Biosphere– geosphere interactions. Palaeogeography, Palaeoclimatology, Palaeoecology 232, 237–250.

Erba, E., Bottini, C., Weissrt, H., Keller, C.E., 2010. Calcareous Nannoplankton Response to Surface-Water Acidification Around Oceanic Anoxic Event 1a. Science 329, 428-432.

Farquhar, G.D., Ehleringer, J. R., Hubick, K. T., 1989. Carbon isotope discrimination and photosynthesis. Annual Review of Plant Physiology and Plant Molecular Biology, 40, 503-538.

Furin, S., Preto, N., Rigo, M., Roghi, M., Gianolla, P., Crowley, J.L., Bowring, S.A., 2006. High- precision U-Pb zircon age from the Triassic of Italy: Implications for the Triassic time scale and the Carnian origin of calcareous nannoplankton and dinosaurs. Geology 34, 1009-1012.

Gianolla, P., Ragazzi, E., Roghi, G., 1998. Upper Triassic amber from the Dolomites (northern Italy). A paleoclimatic indicator? Rivista Italiana di Paleontologia e Stratigrafia 104, 381–390.

Greene et al., 2010

Greene, A.R., Scoates, J.S., Weis, D., Katvala, E.C., Israel, S., Nixon, G.T., 2010. The architecture of oceanic plateaus revealed by the volcanic stratigraphy of the accreted Wrangellia oceanic plateau. Geosphere 6, 47-73.

Hardie 1996;

Hardie, L.A., 1996. Secular variation in seawater chemistry: An explanation for the coupled secular variation in the mineralogies of marine limestones and potash evaporites over the past 600 m.y. Geology 24, 279-283.

Hasiuk and Lohmann, 2010

Hasiuk, F.J., Lohmann, K.C., 2010. Application of calcite Mg partitioning functions to the reconstruction of paleocean Mg/Ca. Geochimica et Cosmochimica Acta 74, 6751–6763.

Hesselbo, S., Jenkyns, H.C., Duarte, L.V., Oliveira, L.C.V., 2007. Carbon-isotope record of the Early Jurassic (Toarcian) Oceanic Anoxic Event from fossil wood and marine carbonate (Lusitanian Basin, Portugal). Earth and Planetary Science Letters 253, 455-470.

Hornung, T., Brandner, R., 2005. Biochronostratigraphy of the Reingraben Turnover (Hallstatt Facies Belt): Local black shale events controlled by regional tectonics, climatic change and plate tectonics. Facies 51, 460-479.

Hornung, T., Krystyn, L., and Brandner, R., 2007a, A Tethys-wide mid-Carnian (Upper Triassic) carbonate productivity decline: evidence for the Alpine Reingraben Event from Spiti (Indian Himalaya): Journal of Asian Earth Sciences, v. 30, p. 285–302.

Hornung, T., Brandner, R., Krystyn, L., Joachimsky, M.M., and Keim, L., 2007b, Multistratigraphic constraints on the NW Tethyan ''Carnian Crisis'': New Mexico Museum of Natural History and Science Bulletins, v. 4, p. 9–67.

Jahren, A.H., Arens, N.C., Harbeson, S.A., 2008. Prediction of atmospheric ∂ 13CO2 using fossil plant tissues. Review of Geophisics 46, RG1002, doi:10.1029/2006RG000219.

Jahren, A.H., 2004. The carbon stable isotope composition of pollen. Review of Palaeobotany and Palynology 132, 291-313.

Jenkyns, H.C., 2010. Geochemistry of oceanic anoxic events. Geochemistry, Geophysics, Geosystems, 11, Q03004, doi:10.1029/2009GC002788.

Keim, L., Spötl, C., Brandner, R., 2006. The aftermath of the Carnian carbonate platform demise: a basinal perspective (Dolomites, Southern Alps). Sedimentology 53, 361–386.

Korte, C., Kozur, H., Veizer, J., 2005. ∂ 13C and ∂ 18O values of Triassic brachiopods and carbonate rocks as proxies for coeval seawater and palaeotemperature. Palaeogeography, Palaeoclimatology, Palaeoecology 226, 287-306.

Kustatscher, E., Manfrin, S., Mietto, P., Posenato, R., Roghi, G., 2006. New biostratigraphic data on Anisian (Middle Triassic) palynomorphs from the Dolomites, Italy. Review of Palaeobotany and Palynology 140, 79-90.

Martinez, R.N., Sereno, P.C., Alcober, O.A., Colombi, C.E., Renne, P.R., Montanez, I.P., Currie, B.S., 2011. A basal dinosaur from the down of the dinosaur era in southwestern Pangea. Science 331, 206-210.

Pagani, M., Caldeira, K., Archer, D., Zachos, J.C., 2006. an ancient carbon mystery. Science 314, 1156-1157.

Pancost, R.D., Boot, C.S., 2004. The palaeoclimatic utility of terrestrial biomarkers in marine sediments. Marine Chemistry 92, 239–261.

Payne, J.L., Lehermann, D.J., Wei, J., Orchard, M.J., Schrag, D.P., Knoll, H.A., 2004. Large perturbations of the carbon cycle during recovery from the end-Permian extinction. Science 305, 506–509.Peters, K., Walters, C.C., Moldowan, J.M., 2005. The Biomarker Guide – Second Edition. Cambridge University Press, 1155pp.

Preto, N., Spotl, C., Mietto, P., Gianolla, P., Riva, A. and Manfrin, S. (2005) Aragonite dissolution, sedimentation rates and carbon isotopes in deep-water hemipelagites (Livinallongo Formation, Middle Triassic, northern Italy). Sed. Geol., 181, 173–194.

Preto, N., Hinnov, L., 2003; Unraveling the origin of carbonate platform cyclothems in the Upper Triassic Durrenstein Formation (Dolomites, Italy). Journal of Sedimentary Research 73, 774–789.

Preto, N., Kustatscher, E., Wignall, P.B., 2010. Triassic climates – State of the art and perspectives. Palaeogeography, Palaeoclimatology, Palaeoecology 290, 1–10.

Ries, J.B., 2010. Review: geological and experimental evidence for secular variation in seawater Mg/Ca (calcite-aragonite seas) and its effects on marine biological calcification. Biogeosciences 7, 2795–2849.

Rigo, M., Preto, N., Roghi, G., Tateo, F., Mietto, P., 2007. A rise in the Carbonate Compensation Depth of western Tethys in the Carnian (Late Triassic): Deep-water evidence for the Carnian Pluvial Event. Palaeogeography, Palaeoclimatology, Palaeoecology 246, 188–205.

Rogers, R.R., Swisher, C.C., III, Sereno, P.C., Monetta, A.M., Forster, C.A., Martinez, R.N., 1993, The Ischigualasto tetrapod assemblage (Late Triassic, Argentina) and 40Ar/39Ar dating of dinosaur origins: Science 260, 794–797.

Roghi, G., 2004. Palynological investigations in the Carnian of the Cave del Predil area (Julian Alps, NE Italy). Review of Palaeobotany and Palynology 132, 1–35.

Roghi, G., Ragazzi, E., Gianolla, P., 2006. Triassic Amber of the Southern Alps. Palaios 21,143- 154.

Roghi, G., Gianolla, P., Minarelli, L., Pilati, C., Preto, N., 2010. Palynological correlation of Carnian humid pulses throughout western Tethys. Palaeogeography, Palaeoclimatology, Palaeoecology 290, 89–106.

Schlager, W., Schöllnberger, W., 1974. Das Prinzip stratigraphischer Wenden in der Schichtfolge der Nördlichen Kalkalpen. Mitteilungen. Österreichische Geologische Gesellschaft 66–67, 165–193.

Simms & Ruffell, 1989 Simms, M.J., and Ruffell, A.H., 1989, Synchroneity of climatic change and extinctions in the Late Triassic. Geology 17, 265–268.

Simms, M.J., Ruffel, A.H., Johnson, L.A., 1995. Biotic and climatic changes in the Carnian (Triassic) of Europe and adjacent areas. In: Fraser, N.C., Sues, H.-D. (Eds.), In the Shadow of the Dinosaurs: Early Mesozoic Tetrapods. Cambridge University Press, pp. 352–365.

Simms, M.J., Ruffell, A.H., 1990. Climatic and biotic change in the late Triassic. Journal of the Geological Society of London 147, 321–327.

Stanley, S.M., Hardie, L.A., 1998. Secular oscillations in the carbonate mineralogy of reef-building and sediment-producing organisms driven by tectonically forced shifts in seawater chemistry. Palaeogeography, Palaeoclimatology, Palaeoecology 144, 3-19.

Stanley Jr., G.D., 1988. The history of early Mesozoic reef communities: a three-step process. Palaios 3, 170–183.

Stanley Jr., G.D., 2003. The evolution of modern corals and their early history. Earth-Sci. Rev. 60, 195–225.

Stefani, M., Furin, S., Gianolla, P., 2010. The changing climate framework and depositional dynamics of Triassic carbonate platforms from the Dolomites. Palaeogeography, Palaeoclimatology, Palaeoecology 290, 43–57.

Taylor, T.N., Taylor, E.L., Krings, M., 2009. Paleobotany - The Biology and Evolution of Fossil Plants, Second Edition. Academic Press, Elsevier, 1230p.

Tipple, B.J., Pagani, M., 2007. The early origin of terrestrial C4 photosynthesis. Annual Review of Earth and Planetary Sciences 35, 435-461.

Tozer, E.T., 1994. Canadian Triassic ammonoid faunas. Geological Survey of Canada, Bulletin 467.

Xie, S., Pancost, R.D., Huang, X., Jiao, D., Lu, L., Huang, J., Yang, F., Evershed, R.P., 2007. Molecular and isotopic evidence for episodic environmental change across the Permo/Triassic boundary at Meishan in South China. Global and Planetary Change 55, 56–65.

Zachos, J.C., Rohl, U., Schellenberg, S.A., Sluijs, A., Hodell, D.A., Kelly, D.C., Thomas, E., Nicolo, M., Raffi, I., Lourens, L.J., McCarren, Dick Kroon, D., 2005. Rapid Acidification of the Ocean During the Paleocene-Eocene Thermal Maximum. Science 308, 1611-1615.